

ATTIRE

(Analytical Tools For Thermal Infrared Engineering)
- A sensor simulation and modeling package

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N 93-22203

1/18/88

P. 19

ABSTRACT

The Advanced Sensor Development Laboratory (ASDL) at the Stennis Space Center develops, maintains and calibrates remote sensing instruments for the National Aeronautics & Space Administration (NASA). To perform system design trade-offs, analysis, and establish system parameters, ASDL has developed a software package for analytical simulation of sensor systems. This package called "Analytical Tools for Thermal InfraRed Engineering" - ATTIRE, simulates the various components of a sensor system. The software allows each subsystem of the sensor to be analyzed independently for its performance. These performance parameters are then integrated to obtain system level information such as Signal-to-Noise Ratio (SNR), Noise Equivalent Radiance (NER), Noise Equivalent Temperature Difference (NETD) etc. This paper describes the uses of the package and the physics that were used to derive the performance parameters.

In addition, ATTIRE can be used as a tutorial for understanding the distribution of thermal flux or solar irradiance over selected bandwidths of the spectrum. This spectrally distributed incident flux can then be analyzed as it propagates through the subsystems that constitute the entire sensor. ATTIRE provides a variety of functions ranging from plotting black-body curves for varying bandwidths and computing the integral flux, to performing transfer function analysis of the sensor system.

The package runs from a menu-driven interface in a PC-DOS environment. Each sub-system of the sensor is represented by windows and icons. A user-friendly mouse-controlled point-and-click interface allows the user to simulate various aspects of a sensor. Several interactive features allow for data plotting and visualization.

The package can simulate a theoretical sensor system. Trade-off studies can be easily done by changing the appropriate parameters and monitoring the effect on the system performance. The package can provide plots of system performance versus any system parameter. A parameter (such as the entrance aperture of the optics) could be varied and its effect on another parameter (e.g., NETD) could be plotted. A third parameter (e.g., the obscuration) could be varied for each plot and several plots obtained on the same graph. The menu for such "Y vs X" plots for different values of "Z" contains various such options. The package also allows the user to create customized work-sheets of the simulated system and save the analysis for interface with other packages.

The emissivity, atmospheric transmission and the optical transmission default as constants over the specified spectral bandwidths. There is an option for making these parameters spectrally variable. If more than one of the above-mentioned three parameters are spectrally variable, then it is possible that the upper and lower wavelength values as well as the resolution of the wavelength array may not be the same for all three arrays. The package performs an interpolation of the data to smooth out the curves and then projects them onto a common wavelength array for all the parameters.

INTRODUCTION

The design of sensor systems and analysis of their performance requires the use of several varied aspects of science and engineering. From the understanding of the laws of electromagnetic radiation to the computation of signal-to-ratios of a sensor, the exercise of sensor analysis and design is ideally suited for computer simulation. In this paper one such software package is described. The package called ATTIRE runs on a PC-DOS platform. It can be used for simulating sensor systems as well as understanding the behavior and interaction of various sub-systems that constitute a sensor. Fig. 1 shows the flow-chart for the energy flow that is modeled by ATTIRE. The sensor is represented by its various parameters as shown.

MENU DRIVEN SYSTEM

The user types 'ATTIRE' from the DOS prompt to enter into the package. The screen contains a flowchart for signal propagation of the energy that will be incident on the sensor. Fig. 2 shows the main menu as it may appear on the screen. The energy originates from a flux source. This source could either be the solar energy or thermal energy from a blackbody. An icon is used to represent the parameters that make up the sensor flux source. On clicking at this icon one enters into another window which displays the characteristics of the parameters that make up the source flux. The source flux energy is then propagated through the next subsystem - the atmosphere. The atmosphere attenuates the radiation coming from the source and also adds some radiation from its constituents due to effects such as scattering. This is followed by the optics at the sensor. The optics focus the energy of the source onto a detector. The detector converts the radiation into electrical energy. The optics sub-system and the electro-optics, i.e., the detector sub-system, are the next two icons in the signal flow. The electrical energy can then be amplified and modified in its bandwidth and noise characteristics. This is represented by the electronics icon. The last icon represents the spatial characteristics of the system, i.e., its dwell time, IFOV etc. The user can click onto either of these icons to enter into these sub-systems.

Apart from these six icons the user encounters the main menu. The main menu is made up of a window. The window can be resized or relocated using a mouse. The mouse is pressed at any of the edges of the window for resizing. The window can also be moved anywhere on the screen by pressing the mouse in the topmost line of the window. The outline of the window appears in the form of a rectangle which can then be moved anywhere.

The window is made up of three items - a listing of the system level parameters on a channel-by-channel basis, six buttons with numbers attached to them and a horizontal menu, .

The listing in the window contains information on the current sensor being analyzed. The listing is done on a channel-by-channel basis. Each channel is identified by its bandwidth. For each channel, the main window shows system level parameters. The energy available from each channel after it is attenuated based on its emissivity or albedo, the atmospheric and optical transmittance, FOV, and the nature of the source (thermal or solar) is computed in energy (W/cm^2) and photon units (photons/s/cm²). The main window also contains the power in watts that is incident on the detector. This is followed by the three system level parameters - SNR, NER, and NETD.

The six buttons are for facilitating the display of a particular channel on the window. This happens when the number of channels is much greater than the window size. Each of these buttons contains a number. When clicking on a button, the channel corresponding to the number in the button is displayed on the top of the window screen. These numbers are programmable by using the item called 'CHAN' in the horizontal menu.

The horizontal menu performs functions to modify or analyze the sensor parameters. The first menu

item 'CHAN' performs three major functions. It allows the user to modify the number of channels in the sensor being analyzed. The maximum number of channels that currently can be processed is 50. The second function of this menu item is to modify the bandwidths of the channels.

The process of modification of any parameter in ATTIRE follows a standard procedure. The user is first prompted with a menu asking if the modification needs to be done for only one channel, a few channels, or for all channels. For the case of one or a few channels, the user is prompted for the number of the channels that need to be modified. A tick mark appears next to the number of the channel. In the case of more than one channel being prompted for, the user can continue to click on the channel numbers. To delete a number that has been tick marked, the user just needs to click on it again. One continues this process until the required channels have been selected. The user then clicks outside the selection windows to accept the selected channels. Also, all the operations in ATTIRE can be done without a mouse control. In the case of channel selections, the up and down arrow keys are used to move within the selected window. If the number of channels is greater than the size of the selected window, the "Page Up" and "Page Down" keys allow for scrolling to other areas of the index. The tick marks are created by typing the "Enter" key. The end of the selection process is signified by the "Control - Enter" keys. After having selected the number of channels that need to be modified, the appropriate parameter is edited.

If only one channel is selected, the existing value of the parameter appears in a window. This value is appropriately edited. If more than one channel is selected, the modification can be done in two ways. The first method just allows for placing the same parameter value in all channels. This procedure is the same as for one-channel selection. The other manner in which the selected parameter can be modified is by placing a linearly increasing series of values in the selected channels. In this case the user is prompted for the initial and final values of the parameter starting from the first to the last selected channel.

The source emissivity, atmospheric transmission, and optical transmission are initially assumed constant over the specified spectral bandwidths. There is an option for making these parameters spectrally variable. If more than one of the above-mentioned three parameters are spectrally variable, then it is possible that the upper and lower wavelength values and the resolution of the wavelength array may not be the same for all three parameters. The software package performs an interpolation of the data to smooth out the curves and then projects them onto a common wavelength array.

The spectrally distributed incident flux can be analyzed as it propagates through the subsystems. Fig. 1 shows the signal flow and the various parameters that affect the performance of the system. Each of the icons on the main menu represent one of these sub-systems.

SUB-SYSTEMS

The software divided the system into the following sub-systems: 'SOURCE FLUX', 'ATMOSPHERICS', 'OPTICS', 'ELECTRO_OPTICS', 'ELECTRONICS' and 'PIXEL PARAMETERS',

The system can be simulated in a multi-spectral manner, i.e as many as 50 channels can be processed simultaneously for performance analysis. For each channel, the parameters corresponding to these sub-systems can be entered. The parameters can be entered one-by-one for each channel or in a linearly varying manner to analyze the effect of varying one parameter on the system performance. Also, all the channels can be made to assume the same value.

Since each channel is modeled independently of the other channels, the package can be used to simulate one 50-channel sensor or 50 unique sensors or any combination in between.

FLUX SOURCE

For analysis of the system a target has to be simulated as a source for the flux signal. This could be either a black body for thermal sources, the solar irradiance for visible/near IR sources or any customized source depending upon the application. Upon entering the menu the user can choose either of these options.

Blackbody Source

The spectral distribution of blackbody radiant exitance in energy units at a given temperature is obtained from Planck's formula

$$F_n(T) = \int_{\Delta\lambda_n} M_{e,\lambda}(\lambda, T) \mathfrak{R}_n(\lambda) d\lambda$$

where

$\Delta\lambda_n$ = spectral bandwidth of channel 'n'.

$\mathfrak{R}_n(\lambda)$ = Relative Responsivity of the sensor for channel 'n'.

$$M_{e,\lambda}(\lambda, T) = \frac{c_1}{\lambda^5 \left(e^{\frac{c_2}{\lambda T}} - 1 \right)} \text{ W cm}^{-2} \mu\text{m}^{-1}$$

where

$$c_1 = 2\pi hc^2 = 3.7483 \times 10^4 \text{ W cm}^{-2} \mu\text{m}^4$$

$$c_2 = \frac{hc}{k} = 1.4388 \times 10^4 \mu\text{m K}$$

h = Planck's constant.

k = Boltzmann constant.

λ = wavelength (μm).

T = temperature of source (K).

(1)

Assuming the source to be Lambertian, the spectral radiance is given by dividing the exitance by π steradians. If the source of the flux is not a blackbody, the spectral radiance is obtained by multiplying by the emissivity of the source as follows

$$L_{e,\lambda}(\lambda,T) = \frac{\epsilon(\lambda)}{\pi} M_{e,\lambda}(\lambda,T)$$

$$= \frac{\epsilon(\lambda)}{\pi} \left(\frac{c_1}{\lambda^5 (e^{\frac{c_2}{\lambda T}} - 1)} \right) \text{ W cm}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$$

where $\epsilon(\lambda)$ = emissivity of the source. (2)

For a field-of-view (FOV) Ω_s , the radiant exitance is given as follows:

$$M_{e,\lambda}(\lambda,T) = (\Omega_s) L_{e,\lambda}(\lambda,T) \text{ Wcm}^{-2} \mu\text{m}^{-1}$$

where Ω_s = Field of View. (3)

Solar Source

Solar radiation can be approximated by a 6,000 K blackbody curve. The solar spectrum is modified by atmospheric transmission as it passes through an air mass en route to the Earth's surface. For an airborne remote sensing system, this energy is further affected by the albedo of the surface type and the atmospheric path back to the sensor system. The spectral distribution of the solar irradiance was compiled from various sources^{1,2} to arrive at a curve for wavelengths ranging from 0.295 to 2.541 μm . The resolution of this curve is 1 nm. This is the solar curve incorporated in the ATTIRE program, and used to calculate the available solar radiation for each reflecting channel. Fig. 3 shows the solar curve.

Modeling of the Source Flux in ATTIRE

ATTIRE provides an icon in the main menu called 'FLUX'. Fig. 4 shows the flux menu as it appears on the screen. On entering this menu from the main menu, another window appears along with a series of icons. These icons allow the user to change the type of flux (Blackbody or Solar), the temperature of the radiating source, the emissivity or reflectivity of the source and the Field-of-View (FOV) of the source. The window contains a horizontal menu whose items allow the user to perform the same operations as the main menu.

The flux type can be changed by clicking on the icon or typing 't' key. On entering the icon, the user is prompted for identifying the type of the flux. If the type is solar, care should be taken that the bandwidths for that channel are within the solar range. The Solar menu contains items that identify the solar flux; i.e., channel bandwidth and reflectivity of the target. The user enters the appropriate bandwidth values and the program picks up the corresponding irradiance values from a file called SOLAR.BIN. It then multiplies each irradiance value by the reflectivity to obtain the effective spectral flux. Selecting the Other Sources menu, the user can enter the source as a specific lamp or any emitting source whose distribution is known.

To obtain spectral radiant exitance for a source radiating uniformly in all directions, the FOV is made π steradians. To obtain spectral radiant exitance at any other solid angle, the appropriate value is entered.

In order to compute radiance, the FOV should be set equal to one steradian or 57.7°. The FOV is modified by clicking on the icon or by typing 'v' key.

If the user has selected a thermal source as the flux, the program uses the temperature assigned for that channel to compute the flux. The temperature icon is used (or typing 't') for that purpose.

The medium between the source and the detector is made up of the atmospheric path and the optical path. The flux passes through the atmosphere before being collected by the optics of the sensor. It then passes through a series of reflective and refractive optical elements before it is incident on the detector.

Depending on the type of flux, the radiation is attenuated by the emissivity for the thermal and the albedo for the solar case. These are modified by clicking on the appropriate menu (or by typing 'e'). This value can be spectrally variable or constant. In the case of spectrally variable values, the user is prompted for a file name. This file name must contain the two arrays - wavelength and emissivity or reflectivity. This is an ASCII file which has these two parameters in each line of the file. The first two lines of the file are ignored and can be used for comments. The data is picked up from the third line. The first number is the wavelength and the second the parameter. The file continues to read until the line it read does not contain two numbers or end-of-file is reached. When a spectrally variable parameter is chosen, the parameters entered in channel bandwidth are not applicable as a wavelength array supplied with the file determines that bandwidth.

ATMOSPHERE

The atmosphere attenuates the amount of flux that enters the sensor. Only a fraction of the flux is incident on the optical aperture. This atmospheric transmission coefficient is denoted by $\tau_a(\lambda)$. It is assumed to be a function of the wavelength.

Also, the atmosphere contributes to the radiance entering the sensor system. This atmospheric path radiance can be divided into two categories, depending on the direction of the flux. The upwelling radiance, $L^A_1(\lambda)$, is the flux from atmospheric particles that is directly incident on the sensor. The downwelling radiance, $L^A_2(\lambda)$, is the flux that is incident on the target. This radiance then is reflected from the target back to the sensor.

Thus the effective flux incident on the sensor is given by:

$$L_\lambda(\lambda, T) = \tau_a(\lambda) [\epsilon(\lambda) L_{e,\lambda}^{BB}(\lambda, T) + L^A_1(\lambda) + (1 - \epsilon(\lambda)) L^A_2(\lambda)] \quad (4)$$

ATTIRE Modeling of the Atmosphere

The atmosphere is selected by clicking on the icon for the 'ATMOSPHERE' in the main menu. Fig. 5 shows the menu as it appears on the screen. This menu contains three items for each channel - transmittance, upwelling and downwelling path radiance. The transmittance is modified in a manner similar to that for the emissivity in the flux sub-menu.

OPTICS

The aim of the optics subsystem is to collect, focus, and disperse the radiant flux from the source. The energy is then focused on the individual detectors. The two parameters that are critical to the collection

of this energy are the area of the collecting optics and the focal length.

The radiance, limited by the solid angle subtended by the ground pixel, is incident on the entrance aperture and determines the irradiance available to the optics. The area of the entrance aperture minus any obscuration is the other limiting factor.

The solid angle is given by

$$\Omega = \frac{A_{\text{pix}}}{a^2} \quad (5)$$

where A_{pix} = area of the ground pixel
 a = distance between the source and the entrance aperture (altitude)

This solid angle must equal the solid angle subtended by the detector on the entrance aperture (invariance theorem).

$$\frac{A_{\text{pix}}}{a^2} = \frac{A_d}{\text{efl}^2}$$

where A_d = area of detector

efl = effective focal length (6)

Depending on the design of the optical system, the entire area of the primary mirror may not be collecting the incident energy. This could be due to an obscuration of the mirror.

$$A_{\text{eff}} = \text{Area of primary mirror} - \text{Area of obscuration}$$

The series of reflective and refractive elements that constitute the optics subsystem are modeled by an optical transmission coefficient $\tau_o(\lambda)$, the effective area of the collecting optics (A_{eff}), and the effective focal length (efl).

In the case of several systems, the energy is focused on the field stop so that the beam can be directed to more than one detector. For such systems, the area of the field stop should be substituted for A_d .

ATTIRE Modeling of the Optics

The main menu of ATTIRE contains an icon for the Optics. On clicking this icon, the user encounters a window that contains the optics parameters. Fig. 6 shows the menu as it appears on the screen. These are the diameter of the entrance aperture, the diameter of the obscuration, the effective focal length, and the optical transmittance.

The diameters are modified by entering into the appropriate menu items. The effective focal length is modified through its menu item. This value is also dependent on the area of the detector and the IFOV of the system. For all the flux to be incident on the detector, the following relationship must hold.

$$\alpha^2 = \frac{A_d}{efl^2}$$

where α = IFOV (7)

Hence, by changing the focal length, the program automatically changes the detector area according to the above equation.

DETECTORS

For a background noise limited infrared photoconductor (BLIP), the theoretical spectral D^* is given by

$$D^*(\lambda) = \frac{\lambda}{2hc \sin \theta_{1/2}} \sqrt{\frac{\eta}{M_p^{BB}(T_B)}} \text{ cm Hz}^{1/2} \text{ W}^{-1}$$

where

η = Quantum efficiency of the detector

$\theta_{1/2}$ = Cold shield half angle (radians)

M_p^{BB} = Photon background noise flux

$$= \int_{pk}^{\lambda} M_{p,\lambda}^{BB}(\lambda, T_B) d\lambda$$

T_B = Background temperature ($^{\circ}\text{K}$)

(8)

The peak D^* of the detector is obtained by substituting for peak wavelength in the above equation. The D^* curve for the detector is now created by linearly extrapolating $D^*(\lambda)$ up to the peak wavelength.

$$D^*(\lambda) = \frac{\lambda}{\lambda_{pk}} D^*(\lambda_{pk}) \text{ cm Hz}^{1/2} \text{ W}^{-1} \quad (9)$$

D^{**} is D^* normalized to cold shield half angle and is given by:

$$D^{**} = D^* \sin \theta_{1/2} \quad (10)$$

ATTIRE modeling of the Electro-Optics

The main menu of ATTIRE contains an icon for the detectors. On clicking this icon the user enters a screen that contains a window for the parameters that make up the detector sub-system. Fig. 7 shows the menu as it appears on the screen. There is an accompanying icon for each parameter which allows the user to change their values. The user can use the theoretical model to simulate the peak D^* . Also, a user-defined peak D^* can be input. If a peak D^* is input, the program automatically adjusts the other parameters, e.g., Quantum Efficiency, to provide the input D^* peak value. The D^* spectral curve is created by drawing a straight line from $\lambda=0$ (where $D^*=0$) to λ_{pk} (where D^*_{pk} is given). The

detector area does not change independently. As discussed, it is dependent on the effective focal length of the optics and the IFOV of the system (Eqn. 7).

PIXEL PARAMETERS

This sub-system models the the pixel geometry as defined by the sensor motion and system spatial IFOV. In the case of airborne scanners, the sensor is mounted on an aircraft, whose velocity and altitude of flight need to be controlled for contiguous scanning.

The pixel size is a function of the altitude (a) and IFOV, and can be computed by

$$\text{Pixel Size} = 2 a \tan\left(\frac{\alpha}{2}\right) \quad (11)$$

where α = angular IFOV
 a = altitude of aircraft in meters

Pixel size can also be determined using the small angle approximation by:

$$\text{Pixel size} = (\text{IFOV}) (a)$$

For contiguous scanning, the time required for one revolution of the scan mirror is equal to the time required for the aircraft to travel forward a distance equal to one IFOV on the ground. Using the small angle approximation for pixel size

$$\frac{1}{n} = \frac{\alpha a}{v} \quad (12)$$

where n = scan speed in rps
 v = aircraft velocity in meters/sec

ATTIRE Modeling of the Spatial Parameters

The spatial parameters are modeled by entering the menu entitled 'PIXEL PARAMETERS'. Fig. 8 shows the menu as it appears on the screen. Since these parameters are interrelated, changing one may also affect the other. This menu contains the following items:

SCAN-SPEED-HT, SCAN-SPEED-VEL, DWELL-TIME, PIXEL-SIZE, and IFOV.

The scan speed is a function of both altitude and velocity (Eqn. 12).

The dwell time is a function of the scan speed, which in turn is a function of the altitude and velocity. In ATTIRE, changing the dwell time affects the scan speed and the velocity only.

$$\begin{aligned} t_d &= \frac{\alpha}{2\pi n} \\ &= \frac{\alpha^2}{2\pi (v/a)} \text{ seconds} \end{aligned} \quad (13)$$

The Pixel menu contains the IFOV, pixel size, altitude, scan speed, velocity and dwell time. Several

of these parameters are inter-dependent. Therefore changing one might affect some of the others as well.

ELECTRONICS

The signal conditioning and preamplifier electronics are modeled for their bandwidth and noise properties. The aim of the sensor design is to be detector-noise limited. In practice, some noise is added by the electronics. Hence the total noise of the system is represented as follows:

$$\text{Noise}_{\text{total}} = \text{Noise}_{\text{detector}} + \text{Noise}_{\text{electronics}}$$

The electronics noise is input as a noise factor. This is defined as the ratio of the total system noise to the noise of the system prior to the electronics. This makes it simple to define the noise as a multiple of the rest of the noise. Also, it indicates the contribution of the electronics to the total system noise. The detector noise is accounted for in the model where the D^* is calculated assuming certain background noise.

The noise of the electronics is defined as follows

$$n_f = \frac{(\text{SNR})_{\text{input}}}{(\text{SNR})_{\text{output}}} \quad (14)$$

The electronics also determines the sampling interval required to sample the analog output of the amplifiers. In the case of aircraft scanners, as stated earlier, the scan speed 'n', the IFOV ' α ', the plane velocity 'v' and the altitude 'a' are related as follows:

$$\begin{aligned} t_d &= \frac{\alpha}{2\pi n} \\ &= \frac{\alpha^2}{2\pi (v/a)} \text{ seconds} \end{aligned} \quad (13)$$

The sampling period is defined by the dwell time of the sensor i.e the time the system spends at each pixel. In the case of a scanner this is given by

The dwell time determines the smallest spatial sampling interval. It is the smallest time interval between which any occurring change can be detected, i.e., any change faster than t_d will not be detected. It is the time interval between two successive pixels. The spatial sampling frequency is the inverse of the dwell time. This means, based on the Nyquist criterion, the largest spatial frequency component present in the signal is one half of the spatial sampling frequency. Thus in order to collect this signal, the bandwidth of the signal conditioning electronics must, at most, be half the spatial sampling frequency.

$$\begin{aligned}
\text{Dwell Time} &= \frac{1}{\text{Spatial Sampling frequency}} \\
\text{Bandwidth} &= \frac{1}{2} \text{ Spatial Sampling frequency.} \\
\Delta f &= \frac{\pi n}{\alpha}
\end{aligned}
\tag{15}$$

ATTIRE modeling of the Electronics

The user enters into the Electronics sub-system by clicking on the icon in the Main Menu. The noise factor and the Electronics Bandwidth can be modified independently for each channel. Fig. 9 shows the menu as it appears on the screen.

COMPUTING THE BAND-PASS FLUX

The spectral radiance incident on the detector (assuming no path radiance) is given by:

$$L_{e,\lambda}(\lambda, T) = \frac{C_1}{\pi} \frac{\epsilon(\lambda) \tau_a(\lambda) \tau_o(\lambda)}{\lambda^5 (\exp(C_2/\lambda T) - 1)} \text{ W cm}^{-2} \text{ sr}^{-1}
\tag{16}$$

The solid angle subtended by the source at the entrance aperture is

$$\begin{aligned}
\frac{A_s}{a^2} &= \Omega_s \text{ steradians} \\
A_{\text{pix}} &= \text{Area of the pixel} \\
&= (\alpha a)^2
\end{aligned}
\tag{17}$$

The total energy incident on the detector is given by

$$M_{(e,\pi)}(\pi, T) = \int_{\lambda_1}^{\lambda_2} M_{e,\lambda}(\lambda, T) d\lambda = \int_{\lambda_1}^{\lambda_2} \Omega_s L_{e,\lambda}(\lambda, T) d\lambda \text{ W cm}^{-2}
\tag{18}$$

where λ_1 and λ_2 are the lower and upper wavelengths of the channel.

For cases where the bandwidth of the channel is defined by a relative spectral responsivity curve, the total energy is given by:

$$\int_{\text{ch\#}} R(\lambda) \left(\frac{\Omega_s}{\pi} \right) \frac{C_1 \epsilon(\lambda) \tau_s(\lambda) \tau_o(\lambda)}{\lambda^5 (\exp(C_2/\lambda T) - 1)} d\lambda \text{ W cm}^{-2}
\tag{19}$$

where $R(\lambda)$ is the relative responsivity curve.

Power Incident on the Detector

The power incident on the detector is obtained by integrating the radiance exiting the imaging lens over the channel bandpass and multiplying the integral by the throughput. This is given by

$$P_d = \left(\int_{\Delta\lambda} \varepsilon(\lambda) \tau_a(\lambda) \tau_o(\lambda) L_\lambda(\lambda, T) d\lambda \right) (\gamma_d)$$

where γ_d , detector throughput is given by

$$= A_d \Omega_d$$

where

A_d = Area of the detector

Ω_d = Solid angle subtended by the detector at lens

$$= \frac{\text{Area of lens}}{(ef)^2}$$

(20)

Rewriting using the above relationships, we obtain

$$P_d = \left(\int_{\Delta\lambda} \varepsilon(\lambda) \tau_a(\lambda) \tau_o(\lambda) L_\lambda(\lambda, T) d\lambda \right) (A_d) (\Omega_d)$$

(21)

Noise Equivalent Detector Power

The noise equivalent power (NEP) of the detector is defined as the power incident on the detector such that the signal-to-noise ratio is unity. The NEP can also be obtained if the broad-band D^* is available.

In this study, the D^* at peak wavelength is modeled. The broad-band D^* can be obtained from the peak spectral D^* as follows:

$$D_{BB}^*(T) = \frac{\int_0^\infty D^*(\lambda) L_{e,\lambda}(\lambda, T) d\lambda}{\int_0^\infty L_{e,\lambda}(\lambda, T) d\lambda}$$

(22)

The NEP is then defined as

$$NEP(T) = \frac{\sqrt{A_d \Delta f}}{D_{BB}^*(T)}$$

where Δf = electronic bandwidth

(23)

Signal-to-Noise Ratio

The signal-to-noise ratio (SNR) of the detector can be obtained as follows:

$$\text{SNR}_d = \frac{P_d}{\text{NEP}} \quad (24)$$

Noise-Equivalent Radiance

The noise equivalent radiance (NER) denotes the required bandpass radiance exiting from the target such that the SNR is equal to unity of the system.

$$\begin{aligned} \text{NER} &= \frac{\text{Bandpass radiance exiting the target}}{\text{SNR}} \\ &= \frac{\int_{\Delta\lambda} L_\lambda(\lambda, T) d\lambda}{\text{SNR}} \end{aligned} \quad (25)$$

Noise-Equivalent Temperature Difference

The radiometric performance of a thermal sensor is determined by its NE Δ T. This is the ability of the sensor to theoretically discriminate between two temperature values. It is defined as the temperature difference required to make the signal-to-noise ratio of the sensor unity.

$$\text{NE}\Delta T = \frac{\Delta T}{\text{SNR}} = \frac{\partial T}{\partial \left(\frac{V_s}{V_n} \right)} = V_n \frac{\partial T}{\partial V_s} \quad (26)$$

where V_s and V_n are the signal and noise voltages respectively.

$$v_s = (\text{solid angle}) \int_{\lambda_1}^{\lambda_2} \mathcal{R}(\lambda) L_\lambda(\lambda, T) d\lambda$$

$$\mathcal{R}(\lambda) = \text{Spectral Resposivity} = \frac{v_n}{\sqrt{A_d \Delta f}} D^*(\lambda) \quad (27)$$

Expanding the expression and substituting the appropriate parameters

$$\text{NE}\Delta T = \frac{\lambda_{pk}}{D^*(\lambda_{pk})} n_f \sqrt{\frac{\Delta f}{A_d}} \left(\frac{e f l^2}{A_{\text{eff}}} \right) \frac{1}{(\text{Integral})} \quad (28)$$

where Integral =

$$\int_{\lambda_1}^{\lambda_2} \tau_a(\lambda) \tau_o(\lambda) \epsilon(\lambda) \lambda \frac{dL_{\lambda}^{BB}(\lambda, T)}{dT} d\lambda \quad (29)$$

GRAPHICS

The program provides extensive graphics capabilities for viewing data parameters. The graphing routines are divided into two categories - PLOT and GRAPH. The GRAPH feature is used exclusively for spectral graphs, i.e., the x-axis is always the wavelength. In the main menu, the GRAPH feature allows for plotting of either the Energy or the Photon Flux versus wavelength. The flux can be plotted for either of the existing channels or for any user-defined set of parameters. The program prompts the user to select one of these two options. If the user desires a spectral plot of a channel, only the channel number is required. In the case of a user-defined graph, the user is prompted for the type of flux (thermal/solar), the temperature (if thermal), the emissivity/albedo, and the FOV.

The graph feature in the FLUX, OPTICS, and ATMOSPHERICS sub-systems are used to graph the spectral emissivity, the optical and atmospheric transmittance respectively. These can be variable or constant depending on the channel. Each of these three sub-systems also allow for an option in their GRAPH Menu to graph all these three spectrally variable parameters on the same graph.

The plot item in the main menu is used to plot non-spectral parameters against each other. One such example is to compute the SNR of the sensor as it varies with the temperature of the source. The user is prompted for the bandwidth of the sensor. All other parameters that enter into computing the SNR are used from a thermal channel. The user is also prompted for that thermal channel number. Next, the range of temperatures over which the data needs to be plotted is asked for.

The other significant feature of the PLOT item is the User-Defined feature. This allows the user to select either of the sensor parameters as it x and y axes. Then for all the existing channels of the sensors the plot is created.

The graphs appear in a resizable windows form. One window displays the graph and the other window the contents of the array that are being graphed. So the user can not only view the graph, but also view the actual values being plotted. The graphs can be resized by pressing the mouse or the edges and sliding it to the required window size. The top right button of the graphics window is used to make the graphics window fill the entire screen. This can also be done by typing the 'f' key (for full screen). On clicking the top right button of the array values window, the user can quit the graphics environment. This can also be done by typing the 'q' key. The array values window can be scrolled up or down to view different parts of the array.

The main menu additionally contains an item for Graph menu to plot the energy or photon flux of all the channels. It also allows the user to plot all the spectrally variable parameters - which might include emissivity and atmospheric & optical transmission for a channel - on the same screen. This item allows for obtaining graphs of spectrally varying parameters. Other graphs can be obtained from the plot menu.

An additional option exists for the user to be able to obtain a hardcopy of these graphs on an HP Laserjet II printer. Fig. 10 shows one such graph. These figures are the screen outputs of ATTIRE. This is the result of plotting the energy flux radiated at various temperatures within two prominent thermal bands - 3-5 and 8-12 microns. At low temperatures, the 8-12 channel has more energy.

However as the temperature of the target increases, the 3-5 channel has more energy. Thus to monitor high temperatures (specifically at temperatures greater than 582K), e.g., volcanoes and forest fires, it is better to use 3-5 micron channel and for low temperatures, e.g., normal earth temperatures, at 300 K the 8-12 micron channel gives a better performance.

PLOT Y vs X

The package can provide plots of system performance versus any system parameter. A parameter X e.g the entrance aperture of the optics, could be varied and its effect on another parameter Y e.g NETD, can be plotted. Another parameter Z e.g the obscuration, could be varied for each plot and several plots obtained on the same graph. The menu for such " Y vs X plots for different values of Z " contains various options in each sub-system. Fig. 11 shows the result of plotting the variation in NETD with temperature for three different thermal channels.

SPECTRALLY VARIABLE PARAMETERS

The emissivity, atmospheric transmission and the optical transmission default as constants over the specified spectral bandwidths. These could also be made variable. Indeed, in typical situations these are spectrally variable parameters. Before entering either of these parameters from their respective menus, the program asks the user if they are variable or a constant. If they are a constant, the number as a fraction of 1 is entered in the box. If it is a variable, the box shows the letters VAR. The software then picks up the spectrally variable curves from the disk and defaults the bandwidths for the channels to the corresponding bandwidth and resolution. In the case of atmospheric transmission, for each channel the curve should be stored in ASCII format as a1.dat, a2.dat, ... a6.dat. Similarly for optical transmission the first letter should be 'o' (o1.dat ..) and for the emissivity it should be 'e' (e1.dat ..). The first two lines of the data files are ignored by the reading routine. These shall be for the user to describe the curve for their purposes. The data shall follow from the third line onwards. Each line contains the wavelength (in microns) and the corresponding parameter (in %). Thus the reading routine picks up the values for the wavelength and the parameter, one at a time from each line until it reaches the end of the file.

Interpolation and Projection

If more than one of the above mentioned three parameters are spectrally variable, then it is possible that the upper and lower wavelength values as well as the resolution of the wavelength array may not be the same for any two out of the three arrays. For example, the emissivity data may be available from 3.0 to 5.0 microns in intervals of .1 micron whereas the optical transmission data may be available from 2.2 to 4.85 microns in intervals of .05 microns. ATTIRE contains a methods for resolving such ambiguities.

The package first checks for these discrepancies before deciding on the least common denominator for the resolution and selecting the lower and upper limits for wavelength such that all the existing points available can be plotted as they were obtained. However doing this results in several gaps in the arrays, e.g in the above example, a resolution of .05 microns and a bandwidth of 2.2 to 5.0 microns is chosen. This leaves blanks in the emissivity array at 2.2 - 3.0 microns as well as at 3.05, 3.15 ... microns.

The package performs an interpolation on the data to smooth out the curves and then projects them onto a common wavelength array for all the parameters. The emissivity from 2.2 to 3 microns is not assumed to be zero throughout but starting from the value at 3.0 microns gradually tends to zero at 2.2 microns. Similarly the emissivity at 3.05 microns is the average of the emissivity at 3.0 and 3.1 microns.

SUMMARY

The design of a visible through thermal IR sensor system requires a detailed analysis of how the input signal propagates through the system. The major components in developing a model for the sensor system are the **source, atmosphere, optics, detector, spatial parameters, and preamplifier electronics**. The final goal of the analysis is to determine the NER for the various spectral channels of a sensor system.

In this paper, a simulation package "ATTIRE", for analyzing sensor systems was introduced. The package runs in a PC-DOS environment and consists of one executable program and several supporting files. The entire package fits on one high-density floppy disk.

ATTIRE is a useful tool for performing design trade offs as it inter relates several aspects of the sensor system to yield performance parameters. It is also useful as a tool for the understanding of the concepts of radiometry.

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2. P. Moon, "Proposed standard Solar-radiation curves for engineering use," *J. Franklin Inst* , Vol. 230 No. 5, pp. 583-617, 1940.

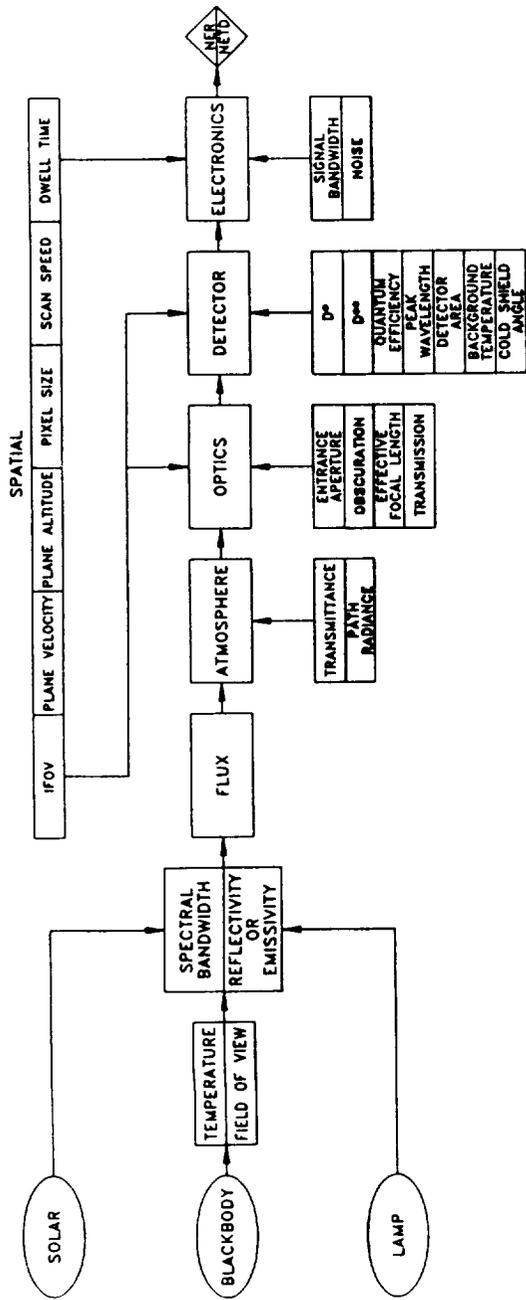


Fig. 1 Flow of energy through a sensor in ATTIRE

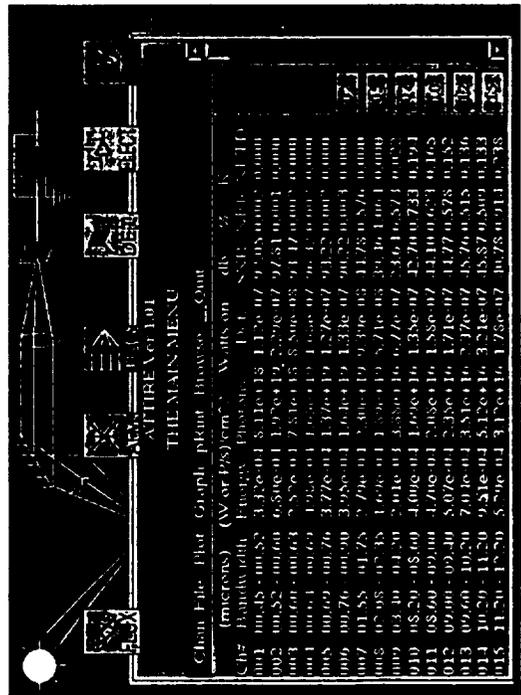


Fig. 2 Main menu of ATTIRE

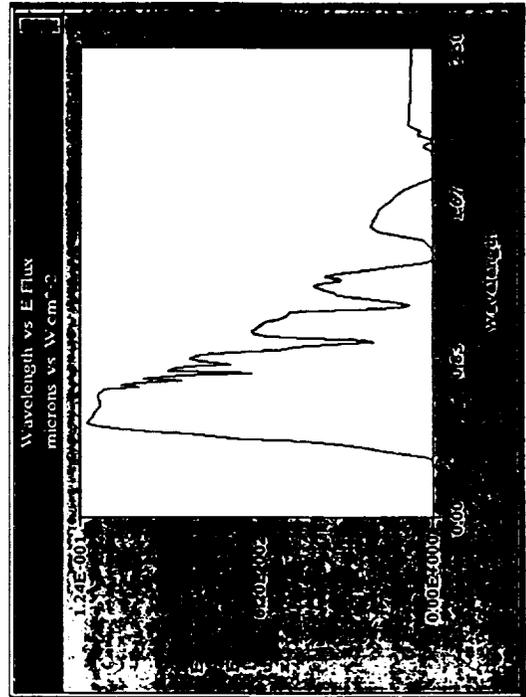


Fig. 3 Solar curve used in ATTIRE

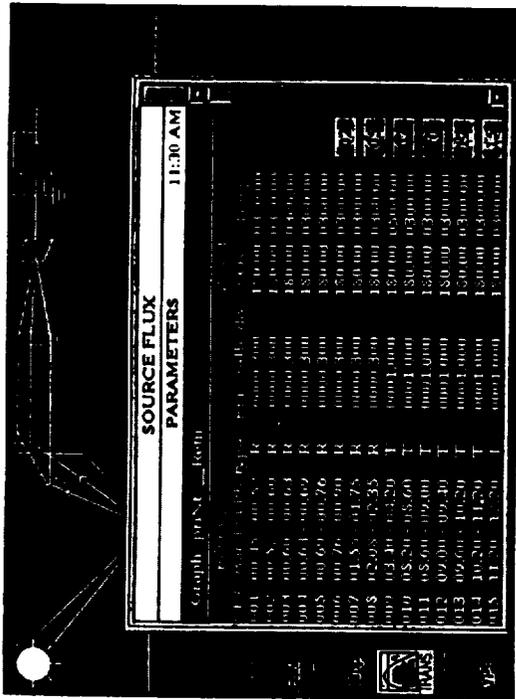


Fig. 4 Source flux menu in ATTIRE

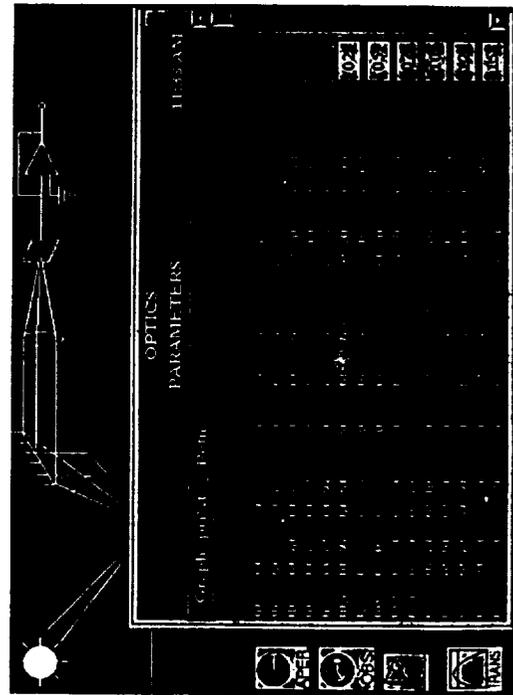


Fig. 6 Optics menu in ATTIRE

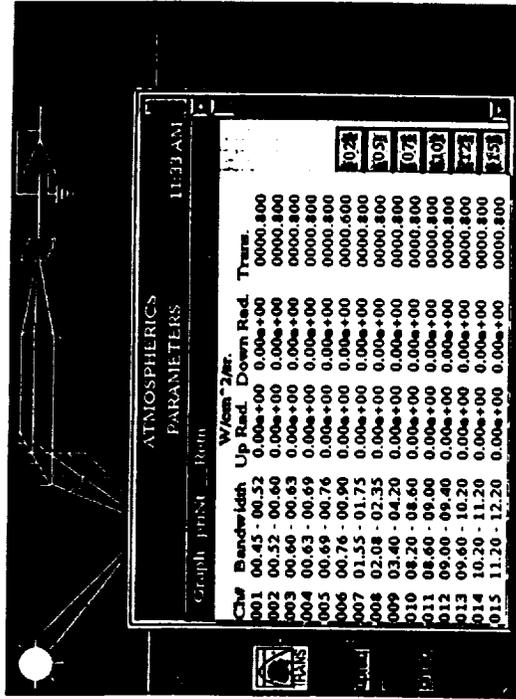


Fig. 5 Atmosphere menu in ATTIRE

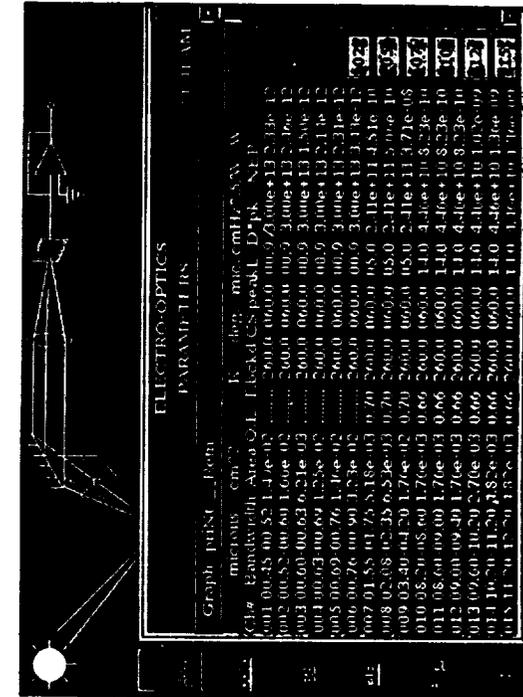


Fig. 7 Electro-optical menu in ATTIRE

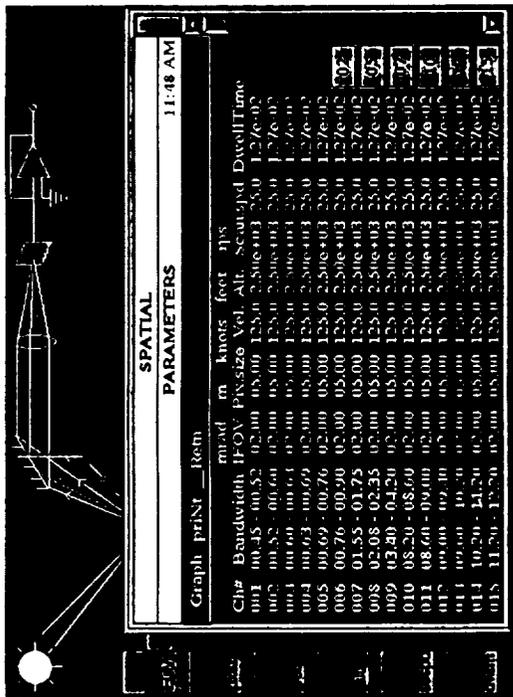


Fig. 8 Spatial parameters menu in ATTIRE

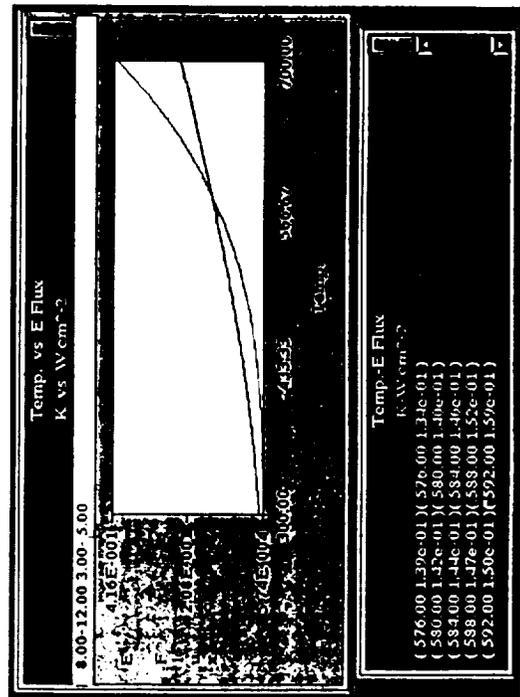


Fig. 10 Energy flux vs temperature for 2 channels

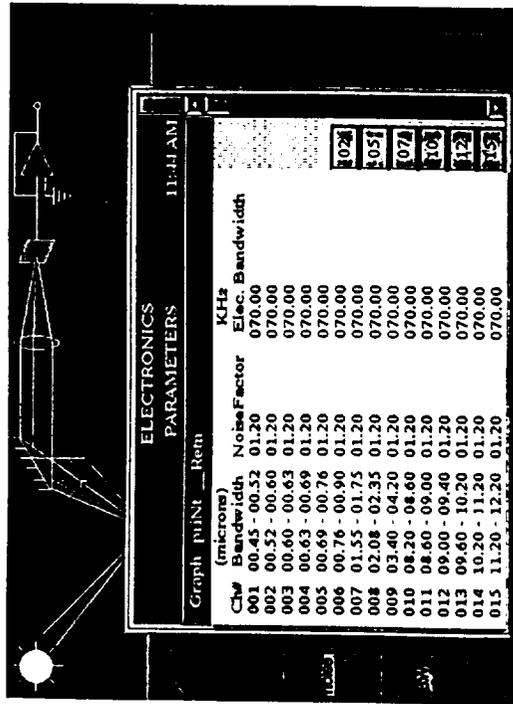


Fig. 9 Electronics menu in ATTIRE

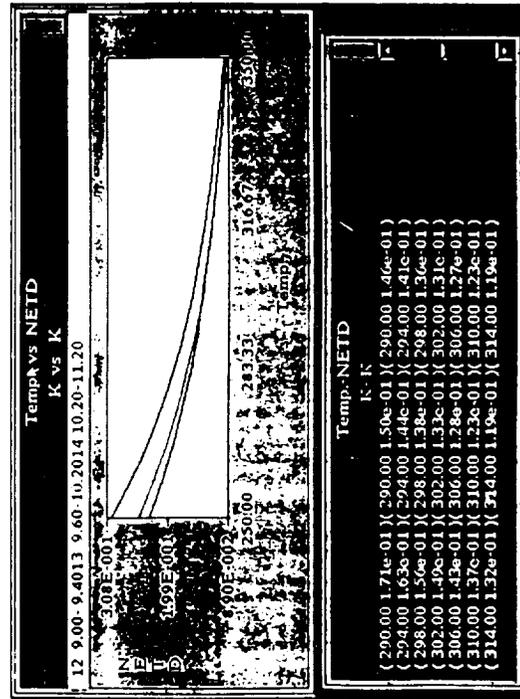


Fig. 11 Plots for variation of NETD vs temperature

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 1993	3. REPORT TYPE AND DATES COVERED CONFERENCE PUBLICATION	
4. TITLE AND SUBTITLE Technology 2002 Volume 2		5. FUNDING NUMBERS	
6. AUTHOR(S) MICHAEL HACKETT, COMPILER		8. PERFORMING ORGANIZATION REPORT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA TECHNOLOGY TRANSFER PROGRAM (CODE CU)		9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) NATIONAL AERONAUTICS AND SPACE ADMINISTRATION WASHINGTON, DC 20546	
		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA CP-3189, VOL. II	
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT UNCLASSIFIED - UNLIMITED SUBJECT CATEGORY 99		12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) Proceedings from symposia of the Technology 2002 Conference and Exposition, December 1-3, 1992, Baltimore, MD. Volume 2 features 60 papers presented during 30 concurrent sessions.			
14. SUBJECT TERMS technology transfer, computer technology, advanced manufacturing, materials science, biotechnology, electronics		15. NUMBER OF PAGES 524	
		16. PRICE CODE A22	
17. SECURITY CLASSIFICATION OF REPORT UNCLASS	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASS	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASS	20. LIMITATION OF ABSTRACT UNLIMITED